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(10) F. W. HEEMSTRA

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In Phase I of the shipboard elevator magnetic sensor investigation, various types of magnetic sensors and detectors were reviewed with regard to their applicability to the elevator problem.

The principles of the two most promising types of magnetic sensor were experimentally studied in greater detail. The principles studied were those of the flux-meter and the flux-gate magnetometer. Of these two, the flux-gate magnetometer principle was selected as the most suitable for the elevator application and development into a prototype sensor.

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20. Abstract (Continued)

Flux-gate magnetometers continuously sense the component of a stationary or slowly varying magnetic field along a chosen axis. The field sensitive element for a small flux-gate sensor is made using a saturable toroidal core with an excitation winding and a symmetrically spaced differentially connected pair of second harmonic detector windings. Small size and high sensitivity is attained with a low excitation power by using commercially available ring cores wound from thin ribbons of nickel-iron alloy.

Preliminary detector circuit designs have been completed for two forms of electronic circuitry being considered. One version includes only passive sensing elements, while the other incorporates some common, industry standard, active electronic components. Breadboard versions of both designs were constructed.

Experiments were conducted on methods of target detection for ferrous (iron or steel) targets and for permanent magnet targets.

With an unmagnetized ferrous target, a permanent magnet is used within the sensor in a magnetic bridge arrangement. The target is detected within a sphere of influence.

With a permanent magnet target, various modes of detection are possible by using the directional properties of both the magnetic field and the flux-gate sensor. The sensor can be made relatively insensitive to the distance of the sensor from the target's line of travel, while precisely indicating displacements along the line. The modes of detection include level or plane detection, error sensing, and precise vertical proximity detection.

Output circuit design still needs to be configured in conformity to control system requirements and the sensing mode to be used.

Conclusions of the magnetic sensor investigation Phase I are that dc or permanent magnetism used with flux-gate magnetic sensors is an excellent detection principle for use in shipboard elevator systems. The technique should be further studied in Phase II by the development of an engineered prototype sensor which has been tested to military certification standards.

CONTENTS

SHIPBOARD ELEVATOR MAGNETIC SENSOR DEVELOPMENT
PHASE I, LABORATORY INVESTIGATIONS

INTRODUCTION

One of the conclusions reached in a study of shipboard weapons elevator controllers by Thomas [1] was that sensors using dc magnetic flux as the physical property to be detected would be the most suitable in the shipboard environment. As a consequence of this conclusion, an investigation of dc magnetic detectors was conducted to determine their feasibility for use in elevator control systems. It was also an objective to conduct experimental studies of magnetic detector types found suitable for this application. The experimental intent was to find a technique for development of a reliable Navy sensor.

FEATURES OF PERMANENT MAGNETIC SENSORS

A number of magnetic sensors in use for various applications use the interaction between alternating magnetic fields and objects of high conductivity (metallic), or of high magnetic permeability (ferrous). Included among these are metal locators, eddy current sensors, and variable reluctance devices. The operation of these sensors is uninhibited by the presence of nonferrous insulating material between the sensor and the object to be detected. Because of the electromagnetic interaction, however, the ac field will not easily pass through conductors.

As distinguished from alternating magnetic field effects, dc or permanent magnetism (as the physical property to be detected) has the following features which make its use attractive:

1. Because the quasi-stationary magnetic field penetrates unimpaired through conductors and insulators alike, any nonferrous material is transparent to the field. In contrast to devices using alternating fields which must be allowed to penetrate for detection, a dc magnetic detector can be made virtually impervious to all but very low-frequency electromagnetic radiation by using conductive shielding.

2. Since the source of the field may be a permanent magnet, it requires no electronics, power, or electrical connections and can be made very strong compared to ac electromagnetic sources.

3. The magnetic field is a vector quantity whose direction and sense is determined by geometry rather than source intensity. It is possible to use the directional properties of the field to determine geometrical relationships between a magnetic target and the detector, independently of the sensitivity of the detector or the strength of the source. This will be explained later in this report.

4. In common with other magnetic sensors, but in contrast to devices using optical or ultra-acoustic windows, the operation of permanent magnetic sensors is unimpaired by paint or grease.

Manuscript Submitted June 10, 1981.

REVIEW OF MAGNETIC DETECTORS

This brief review of magnetic detectors is confined to methods of detection of stationary or slowly varying fields. Methods that are exclusively applicable to alternating fields are not considered in this report.

Forces and Torques

The oldest method of detecting the presence of a magnetic field is by the forces or torques exerted on ferromagnetic objects or electrical circuits. Indeed, the existence of a magnetic field around wires carrying an electric current was first demonstrated with a compass needle. Such forces exist whenever a displacement in the direction of the force would decrease the magnetic field energy. In a magnetic circuit these forces are such as to decrease the reluctance. Thus, in a magnetically operated relay, a force exists which tends to close the air gap in the magnetic path.

Magnetically activated reed switches operate on this principle and, for a magnetized target, may be regarded as proximity switches.

In a somewhat more complex magnetically activated proximity switch ("GO-Switch" by General Equipment Manufacturing Company) a target of ferromagnetic material is used, but it need not be permanently magnetized since the magnetomotive force is supplied by internal magnets. In this device a double throw switch is held in a stable state by the stronger of two opposing forces. A ferromagnetic target in close proximity creates a low reluctance external flux path to weaken the holding force, and the switch is thrown into the opposite state by the opposing magnetic force. A hysteresis is inherent in such an arrangement; that is, the range at which the switch releases is greater than the range of activation.

Because of their simplicity and low cost, these devices deserve careful consideration in regard to their suitability for this application.

Fluxmeter

The flux-meter is an instrument that indicates a cumulative total of magnetic flux of induction threading through a test coil. The total increase or decrease of flux is measured relative to a starting time when the meter is set to zero.

The working principle can be illustrated by the Grassot Fluxmeter, an old instrument traditionally used for measuring the magnetic properties of iron and steel. The meter consists of a D'Arsenval type galvanometer with a nearly torsionless suspension and a very high critical damping resistance. When connected to the low resistance test coil, the meter is greatly overdamped so that free motion is extremely slow. When magnetic flux enters or leaves the test coil, however, the deflection is quick and responsive. The motion is such that the change of flux-turns in the galvanometer coil is equal and opposite to that in the test coil. In other words, electromagnetic forces move the galvanometer coil to such a position that the flux threading the entire circuit is constant.

In the previous example, the galvanometer may be thought of as an integrating device. While the flux is changing in the test coil an electromotive force, E, is induced in the circuit as given by:

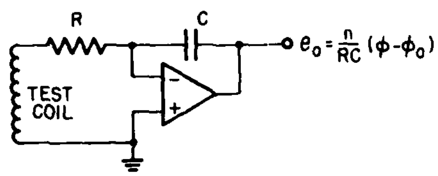
$$E = n\frac{d\phi}{dt} \quad \text{(electromagnetic units)}$$

where, n = number of turns of wire on coil
ϕ = magnetic flux threading the coil (Maxwells)
t = time (seconds)

The meter, therefore, indicates the time integral,

$$n(\phi - \phi_o) = \int_o^t E\,dt$$

of the induced voltage. Obviously, with modern electronics, this meter can be replaced with a simple integrator circuit using an operational amplifier as shown:



Because of the cumulative nature of this device, there appears to be an inherent difficulty for our application because errors are also cumulative and would cause a long-term drift. If a simple way could be found to overcome or avoid the drift problem, the simplicity of this device would make it highly attractive for use as a magnetic detector.

Hall Effect

The Hall effect is a more subtle effect of a magnetic field that results from its effect on the motions of charged particles or carriers of electricity. When an electric current is flowing in a steady magnetic field, an electromotive force is developed which is proportional to the vector product of the current and the magnetic field intensity. This product is a vector whose direction is perpendicular to that of both the current and the magnetic intensity and the magnitude is their product times the sine of the angle between them.

The proportionality constant between the electromotive force (EMF) and the previous vector product is determined by the material through which the current is flowing and is called the Hall-effect coefficient of the material. At best, these coefficients are small. In practical Hall-effect transducers utilizing conductors and semiconductors (such as bismuth, germanium and silicon) the coefficients given an electrical potential in the order of millivolts per hundred gauss of magnetic intensity. Hall coefficients vary with temperature.

Further complications may arise from Von Ettinghausen's effect in which a temperature gradient appears in the opposite direction of the Hall EMF. Thus, thermoelectric potentials will also be produced if the Hall potential electrodes are of dissimilar material.

A magnetic detector based on the Hall effect appears to be practical for strong fields of at least several hundreds gauss. Greater sensitivity could be obtained by using high gain dc amplifiers but not without the attendant problems of dc temperature drift.

Flux-Gate Magnetometer

The flux-gate magnetometer is a magnetic field sensing device which makes use of the high magnetic permeability of nickel-iron alloys such as Permalloy. In contrast to the low sensitivity of Hall-effect devices, this type of sensor can be made extremely sensitive. Highly refined versions of it have been used by the Navy in airborne magnetic anomaly detection (MAD) equipment for submarine detection.

The field sensitive elements in early forms of flux-gate magnetometers consisted of two parallel nickel-iron alloy strips with windings of copper wire for ac excitation and differentially connected detector windings. Later forms of this magnetometer described by Geiger [2] use a single laminated or tape wound ring core instead of the parallel strips. This development greatly reduces the excitation current requirements and the dimensions of the sensing element.

Principles of Operation

The ring core has an excitation winding on each semicircular side of an arbitrary diametrical axis, and they are symetrically spaced with respect to the axis. These coils are connected through current-limiting resistors to a source of ac voltage. The polarity, or phasing of the connections is such that the magnetizing fields of the two coils aid each other to circularly magnetize the ring core.

Because of the low coil resistance and core reluctance, the voltage induced by the rate of change of flux in the core is approximately equal to the applied voltage. As in the case of the flux meter, the quantity of magnetic flux of induction threading the coils is the time integral of the voltage in electromagnetic units (e.m.u.) per turn induced in them. In the flux-gate magnetometer the voltage per turn and the ac frequency are adjusted so that this integral divided by the cross-sectional area reaches the saturation flux density of the core material during each half cycle of the ac excitation voltage. When this saturation level is reached, the voltage drops to zero because the flux can no longer increase. The supply voltage is then dropped across the current limiting resistors.

A pair of detector windings symmetrical about the same axis is connected in series so that the voltages induced by the excitation flux oppose each other and cancel in the detector circuit.

If an external magnetic field having a component along the axis of symmetry exists, it will strengthen the excitation field on one side of the ring core and weaken it on the other. As a result, the side being aided by the external field will reach saturation and its voltage will drop to zero before the weakened side does. During the time interval that only one side is saturated, the induced voltages in the detector windings do not cancel each other and a voltage spike is produced in the detector circuit. On the opposite half-cycle of ac excitation voltage, the opposite side of the core reaches saturation first; but, since the induced voltages are also reversed, the voltage spikes in the detector circuit maintain the same polarity on each half-cycle.

These voltage spikes constitute even harmonics of the excitation frequency. If the detector circuit is tuned to the second harmonic of the excitation frequency, a sinusoidal ac signal is received whose amplitude is proportional to the component of the external magnetic field intensity along the diametrical axis of the symmetry. If the magnetic field is reversed, the phase of the signal also reverses.

Because the core material is driven into saturation, there are no magnetic memory effects even from direct contact with a strong magnet.

Implementation

In its basic form, the ring-core form of flux-gate magnetometer is amazingly simple. By using commercially available cores wound from thin ribbons of nickel-iron alloy, excitation frequencies of 5 to 10 kHz and ring diameters as small as 1/2 in. are feasible. The oscillator or ac excitation source must have sufficient power to drive the core well into saturation.

Detector circuitry may take many forms depending on the application and sensitivity required. Sensitivity may be greatly increased by the use of a tuned ac signal amplifier with a narrow bandwidth. It is possible to use two sets of detector windings with perpendicular axes on the same ring, to simultaneously detect the two magnetic field components in the plane of the ring.

Where only the intensity of a magnetic field component is measured, amplitude detection (rectification) is all that is required. Where the sense of the field component must also be known, a phase sensitive demodulator must be used. The reference phase for this process is generated directly from the excitation voltage as a second harmonic.

Because of its simplicity, sensitivity, and directional sensing capability, the working principle of the ring-core flux-gate magnetometer is a promising candidate for application in a magnetically activated proximity sensor.

Other Magnetometers

There are many other types of magnetometers which, because of their complexity or other undesirable features, will not be given consideration for the proximity sensor application. Included among these are:

Optically Pumped Devices such as Rubidium or Cesium Vapor and Ortho-Helium Magnetometers

These are total field magnetometers based on the Zeeman effect in the fine line structure of spectral emissions. They require a complexity of both optical and very high frequency electronic equipment.

Proton Precession Magnetometer

This is another total field instrument which is characterized by pulsed operation at a very low data rate. It cannot be operated in the presence of magnetic field gradients of the magnitude that exist inside of steel structures such as ships.

Faraday Effect

This is the rotation of a plane of polarization of monochromatic light in some materials by a magnetic field parallel to the direction of light propagation. The effect has also been noted at microwave frequencies in ferrites. The instrumentation required to detect the small angles of rotation is considered too complex for the sensor application.

Josephson Junction Magnetometer

This is an untrasensitive, superconducting, quantum electronic device requiring cryogenic temperatures.

Electron Beam Deflection Magnetometer

This device would require fabrication of a special high vacuum electron tube and the use of relatively high voltages. As with other electron tubes, there is an inherent susceptibility to burned-out filaments and damage from shock and vibration. Physical size is also an important consideration.

OBJECTIVES OF INVESTIGATION

This investigation was conducted, not for the purpose of testing proximity switches already in use, but with the objective of establishing a technique for the development of a reliable Naval sensor which is not dependent on commercial proprietary devices.

Of the magnetic detectors reviewed, only the magnetically activated mechanical switch is currently in use by the Navy as a proximity switch. This switch ("GO-switch" by General Equipment Manufacturing Company) is such a proprietary device having a sole source. Little can be done by way of modification or improvement of the principle incorporated in this switch which could not be regarded as an infringement.

Mechanical switches generally have the disadvantage of being difficult to immunize against shock and vibration, and the requirements for range and repeatability suggest the need for close tolerances in both mechanical and magnetic properties. To attempt the development of a new form of a magnetically activated mechanical switch is not considered likely to be a fruitful endeavor.

Because practical Hall-effect transducers require special materials such as silicon, having a high Hall coefficient, and low-level amplifier circuitry and compensation for temperature variations, such devices are best fabricated by the processes used in semi-conductor integrated circuits. Hall-effect transducers made this way are commercially available (such as the 9SS series Hall-effect transducers made by Micro Switch, a Honeywell Division). High technology techniques are used in the design and fabrication of these proprietary devices.

Although amplifier circuits are integrated into the devices, their sensitivity is still too low (7.5 mV per gauss) to be attractive for use as magnetic proximity detectors to ranges of 20 mm.

Of the remaining types of magnetic detectors, the fluxmeter and the Flux-gate magnetometer appear to be the most adaptable to a proximity switch application. These were selected for further investigation by experimental methods with the intent of developing the principles, techniques and circuitry for a practical magnetic proximity sensor.

EXPERIMENTS

Fluxmeter

A simple integrating fluxmeter, (Fig. 1) containing a single type 741 operational amplifier was built for experimental purposes. The test coil consists of 60 turns of wire on a 1-3/8 in. diameter form. With this number of turns and the integration time constant shown (0.54 millisecond), the sensitivity is calculated to be:

$$\frac{n}{RC} \times 10^{-8} = 1.1 \text{ millivolts per Maxwell}$$

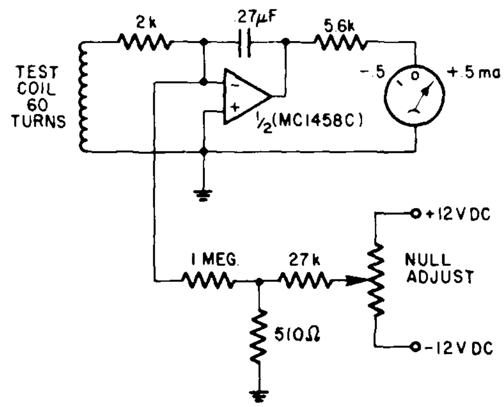


Fig. 1 — Fluxmeter

This was deliberately made low to give a full scale reading when a magnet is inserted into the coil for studying drift problems. The sensitivity can be increased by: (1) increasing the number of turns and (2) decreasing the RC time constant.

Results

To avoid a drift in the output with no flux changes in the coil, the input offset voltage of the operational amplifier must be carefully nulled. Providing that the output is nulled, the fluxmeter performs its designed function of indicating full scale output when the magnet is placed in the test coil and returning to zero when the magnetic flux is withdrawn. However, the meter would not maintain a full scale reading for long periods of elapsed time between these operations and would then return to the negative side of zero when the magnet was withdrawn.

The Problem

These results were expected because: 1. The integrating circuit integrates any and all voltages appearing at the input from any source. No matter how carefully offset voltages are nulled, the error can never be zero and the long-term integration of this error constitutes a drift in the output. Furthermore, the offset null can be expected to be temperature dependent.

2. Any capacitor used in the integrator circuit will have some leakage, however small. As the capacitor loses its charge, in effect, the fluxmeter loses its memory of the amount of flux threading the coil. Thus, when the flux is removed from the coil, the change is integrated in the reverse direction to a negative output reading. This leakage effect always tends to restore the output to zero. It therefore opposes the drift due to offsets and results in some long term equilibrium output voltage.

Possible Solutions

Two ways of resolving the problems of leakage and drift are: 1. Deliberately provide a leakage resistance across the integrating capacitor so that any drift due to offset is overcompensated by the leakage and the equilibrium output voltage is somewhere near zero. Then provide some form of digital memory, such as a flip-flop which is set when a positive integration of sufficient magnitude takes place, indicating proximity of the target. The flip-flop would be reset on a negative integration indicating that the target has left.

The drawback of such a method is that there is no true indication of the presence of a target but only a memory of the last change of status. This dependence on memory is not a satisfactory sensing system because a momentary loss of power would result in loss of knowledge of target position. A device which either continuously senses or periodically updates the targets proximity is more desirable.

2. A way of periodically updating the targets proximity using a fluxmeter would be to periodically reverse the direction of the flux emanating from the target. If the period of the reversal is small compared to the decay time constant of the integrating capacitor due to leakage, then the output would be nearly a square wave and its amplitude would be proportional to the magnetic flux.

Such a scheme would require a switched electromagnet and lose some of the advantages of dc or permanent magnet sources. Not only would it complicate an otherwise simple device but then it also becomes an alternating field sensor, however low the frequency.

A far more efficient and superior method of using ac excitation fields is within the sensing element itself as exemplified by a flux-gate magnetometer.

Although attractively simple, the fluxmeter must be disqualified as a practical proximity sensor and will be relegated to use in laboratory measurements of magnetic flux.

Ring Core Magnetic Sensor

Experiments were conducted on magnetic detection based on the principles described for flux-gate magnetometers in the Review of Magnetic Detectors using high permeability ring-cores. Experimental detector circuitry was also devised, constructed and tested.

Sensing Head

The core used for most of the experimental work was a commercially available torroidal core 3/4 in. o.d., 5/8 in. i.d. wound from 1 mil. Deltamax ribbon 1/8 in. wide and encased in plastic. These cores are normally used in a variety of electromagnetic devices such as saturable core reactors, current transformers, pulse transformers, peaking transformers and filters.

Many different winding arrangements for the excitation and detector circuitry, including a bridge circuit connection were tried, with the conclusion that more elaborate coil arrangements had no significant advantages. The one shown in Fig. 2(a) was selected. The single-ended excitation and detector connections are more adaptable to a variety of circuitry.

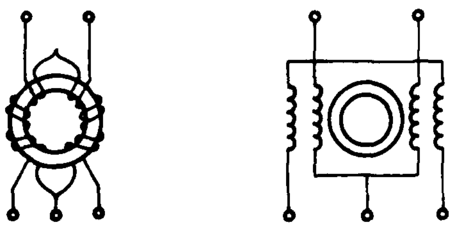


Fig. 2(a) — Winding arrangement of sensing head and schematic representation

Preliminary Experiments

Initial experiments were conducted using a signal generator as the source of excitation and an oscilloscope as a detector to study the relationships between excitation voltage, frequency, and current limiting resistance values versus sensitivity. It was found that for any given excitation voltage, the voltage spikes at the output of the detector windings were maximized if the frequency was adjusted so that saturation occurred near the peak of each half-cycle of excitation voltage. Also, if this relationship between voltage and frequency were maintained, the amplitude of the spikes increased approximately as the square of the frequency. This last result is believed to be due to the combined effect of an increase in both the excitation voltage and in the rate of transfer of unopposed flux of induction (volt-seconds) to the detector circuit.

Although the core is still usable at higher frequencies, an arbitrary frequency of 5 kHz was chosen as the excitation frequency with excellent results. At this frequency, the optimum excitation voltage is 0.1 to 0.2 peak ac volts per turn of wire on each of the excitation windings. The voltage is not critical and is dependent on the core size and material.

When maximum flux density in the core is reached, a sufficient magnetizing force must be generated to drive the core well into saturation. This magnetizing force is generated by the ampere-turns obtained when the voltage across the windings drops to zero. It is limited by the current limiting resistors and the current capability of the excitation source.

Second Harmonic Sensor

A series resonant LC circuit tuned to the 10 kHz second harmonic frequency was added to the detector winding of the sensing head, as shown in Fig. 2(b). This serves to transform the voltage and impedance of the second harmonics generated in the detector coils. Because of the very low source impedance, this method of extracting the signal greatly enhances the output level. A sinusoidal 10 kHz ac output signal of several volts was obtained with an external magnetic field intensity in the order of 10 gauss (about 1 in. from a small magnet).

The sensor was found to be unhampered by the presence of strong magnetic gradients. The signal disappears when the external field is stronger than the magnetizing field of the excitation coils and occurs only when a magnet is in nearly direct contact with the core. The signal is recovered instantly when the magnet is withdrawn.

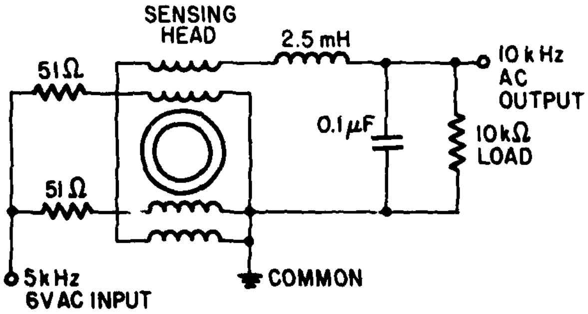


Fig. 2(b) — Second harmonic magnetic sensor

Phase Sensitive Detector

The addition of a diode detector output circuit and an oscillator for the source of excitation to the circuit illustrated would result in a complete magnetometer with dc output proportional to the axial component of magnetic field intensity. However, it would not be able to determine the sense of the component. Detector circuitry for determining whether the magnetic component is positive or negative is possible by making use of the polarity of the voltage spikes generated in the detector coils. This requires a phase sensitive detector circuit.

Figure 3 illustrates a phase sensitive detector arrangement. Figure 4 shows the schematic diagram of a passive phase sensitive detector circuit with dc output. The polarity of the output voltage indicates the polarity of the magnetic field component.

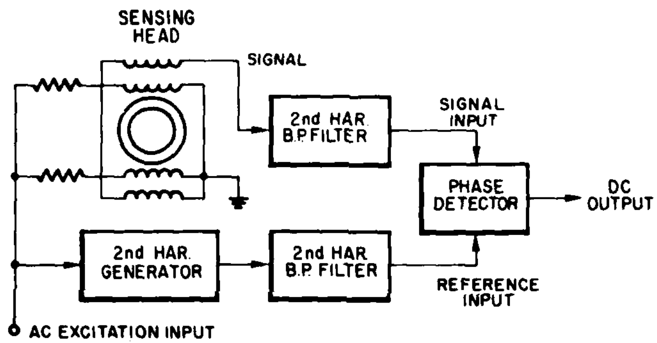


Fig. 3 — Phase sensitive magnetic detector

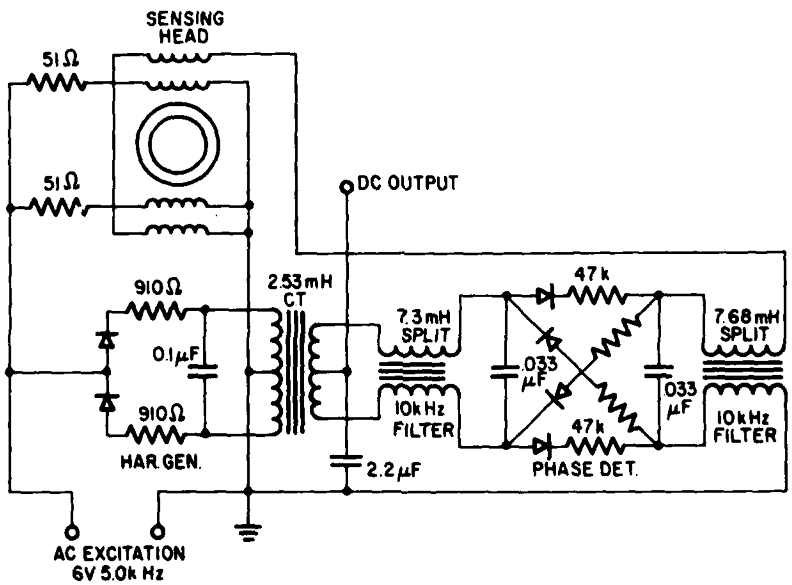


Fig. 4 — Passive phase sensitive magnetic detector circuit

In the circuit, a second harmonic reference voltage is generated from the excitation voltage for switching the diodes in a phase detector. The second harmonic reference is generated by a full wave rectifier using a tuned transformer arrangement. The second filter stage is required to prevent a quadrature phase relationship with the detector signal. The balanced filter inputs to the phase detector allow the ac signals to be cancelled in the output.

The reference voltage could just as well be generated by a second ring core sensing head placed in a magnetic field or having a dc winding. The output of the phase detector would then indicate the weaker of the two field intensities and the polarity of the output would depend on whether the magnetic field components are of like or unlike polarity. This scheme can be used in a device to be discussed later in this report.

Active Circuits

The detector circuit described has only passive components. The power is derived indirectly from the ac excitation. A passive circuit has the advantage of greater reliability and long life, is generally easier to analyze, and often involves fewer components. This circuit has the disadvantage of a tuned transformer and inductors which must be wound to specifications.

The general scheme of Fig. 3 may also be implemented using active filters and an active phase detector to eliminate all transformers and inductors. Active versions of these circuits (Fig. 5) were

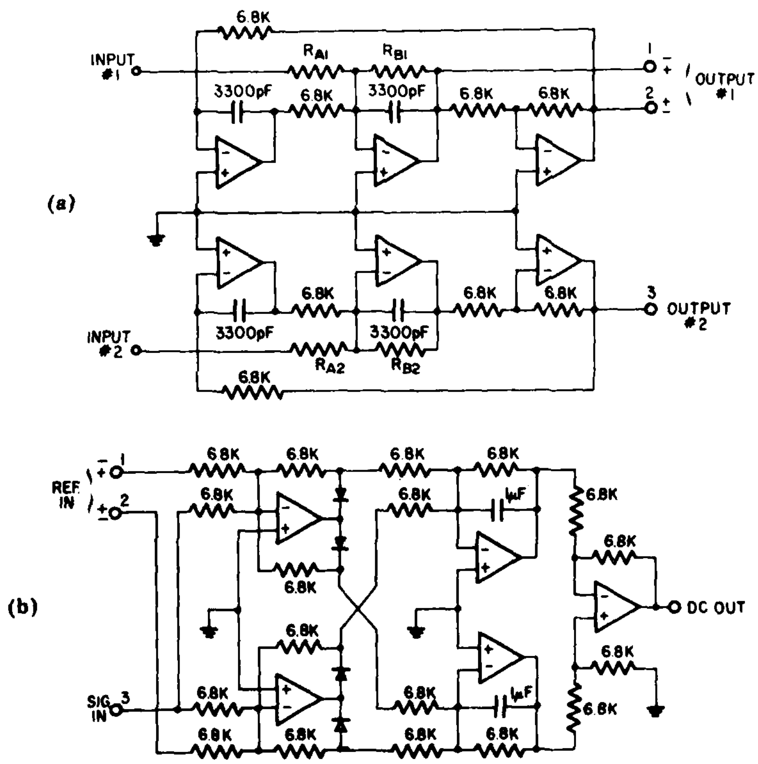


Fig. 5 — (a) Dual active bandpass filter and
(b) Active low level phase detector

built using breadboard construction and they performed well. A lower frequency of operation may be necessary in the active version if low-cost industry standard integrated circuits are to be used.

State-variable, second order band pass active filters of the "bi-quad" configuration were used for the second harmonic filters. This type requires three operational amplifiers but was chosen because of their excellent stability at very narrow bandwidth (or high Q) and the band center frequency may be adjusted independently of the bandwidth and gain with separate sets of resistor values. A phase shifting section is not required for the reference voltage in the active filter version because the correct phase is obtained directly.

The active version of the phase detector also uses operational amplifiers in what are referred to as "precision rectifier" circuits. In these circuits, positive and negative outputs of the rectified input signal are obtained in which the voltage drop across the diodes is automatically corrected in the output by feedback. They will perform well even at low signal levels of a few millivolts. The reference and signal voltage are added in one precision rectifier and a second one rectifies their difference. The outputs are then cross-coupled into a differential amplifier circuit. Functionally, this transformerless circuit is the same as a double balanced ring modulator. Because of the precision rectifier feature, this circuit may be used for phase comparison of two low-level signals.

Other advantages of an active magnetometer circuit are that the circuit parameters are easier to adjust, and it has gain, thus reducing signal power requirements. The disadvantages are that the active circuit is schematically more complicated, requires more components with lower reliability, and it is estimated that a packaged version will require more space.

MAGNETIC TARGET PROXIMITY AND LEVEL DETECTION

Before proceeding further in the development of a magnetometer as a proximity sensor, it is advisable to consider the nature of the target to be detected, to examine the proximity concept as it relates to vector fields, and to define the quantities indicated by the sensor.

The target for a magnetic sensor may be a strongly magnetized object such as an Alnico magnet. It is possible to use the principle of induced magnetism with a soft iron target and a source of magnetomotive force (a magnet) contained within the sensor. A strongly magnetized or "active" target is considered first.

Field of Magnet

Since the flux-gate sensor indicates the component of a magnetic field in the direction of its axis of symmetry, its response to a magnetic target is dependent on its orientation relative to that of the magnet as well as to distance. To study this response it is necessary to resolve the field of the magnet into orthogonal components.

For the limiting case of a simple magnetic dipole moment (separation of the magnetic poles is small compared to the distance) the mathematical treatment is also simple. The result is that for a dipole moment, μ, directed along the z-axis, in cylindrical coordinates with the dipole at the origin, the radial component of magnetic intensity is:

$$H_r = \mu \cdot \frac{3zr}{(z^2 + r^2)^{3/2}}$$

and the axial component is:

$$Hz = \mu \cdot \frac{2z^2 - r^2}{(z^2 + r^2)^{3/2}} \ .$$

The first equation shows that the component directed radially outward from the axis of the dipole reverses direction at the plane $z = 0$. The component is directed outward above this plane and inward below the plane. The second equation defines an angle, $\pm\arctan z/r = \pm 35°$ with respect to the $z = 0$ plane, within which the axial component has a negative direction. Thus, if a fixed distance, d, is maintained from the axis through the dipole, the component is positive whenever the absolute axial distance is greater than $d/\sqrt{2}$ from the $z = 0$ plane, and negative when it is less.

At great distances from the dipole, both components go to zero; but within a range of proximity established by a negative axial component, the $z = 0$ plane is indicated by a radial component of zero, and the sign and magnitude of this component is an indication of position relative to the plane.

The above analysis is useful as an illustration of the nature of magnetic target detection and also establishes a principle which may be applied to level detection. These field equations, however, are not valid for a magnet where the separation of the poles is not small compared to the distance of the sensor. Field mapping of a real magnet in close proximity is done effectively by direct measurement using the flux-gate sensing head and detector circuit.

To enhance the effect of pole separation, two small horseshoe magnets were joined by a 2 in. bar of soft iron as shown in Fig. 6(a). A z-axis and an x-axis are indicated on the figure. Figures 6(b), 6(c) and 6(d) show relative detector output levels for the x- and z-components as a function of z for fixed values of x equal to 1 in., 2 in., and 3 in.

It should be pointed out that, because the relative magnitudes of the field components are determined entirely by the geometrical configuration, all of the units of distance may be arbitrarily scaled by any factor, resulting in the same curve. Only the absolute magnitude is affected by the scale and the strength of the source.

It is seen that the axial (z-axis) range over which the z-component is reversed spreads much more slowly than was found for the analogy of a small dipole at long range. It should also be noted that, over a large portion of this range, the x-component of magnetic intensity is nearly proportional to the z-axis displacement in both sign and magnitude. It is clear that for a known magnetic target geometry, the position along a line of travel parallel to the z-axis can be determined near the target by the signs and relative magnitudes of orthogonal field components.

Applications with a Magnetized Target

The theory of a ring-core flux-gate magnetometer allows the simultaneous measurement of two orthogonal field components with a single ring-core by using two sets of detector winding whose axes of symmetry are perpendicular. Two phase-detector circuits are needed but the excitation and reference voltage requirements are not doubled. A practical magnetic proximity sensor which uses two components of the field is feasible.

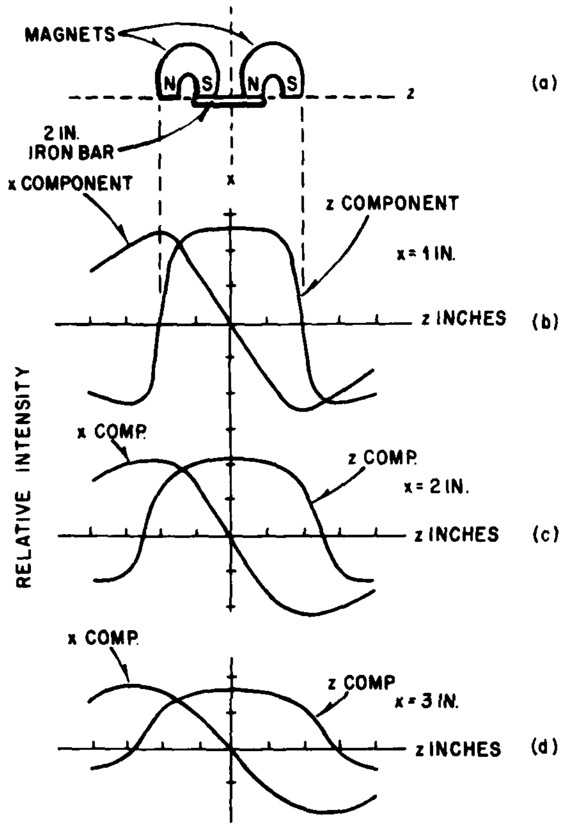


Fig. 6 — Field components of a magnet

Closed Loop Control

The x-component of a magnetized target as illustrated in Fig. 6 appears to be ideally suited to use as an error signal in closed loop control systems for positioning machinery in the shortest time with minimum error and overshoot. While such sophisticated control systems are used extensively in military equipment (as in automatic training of weapons) they require variable speed or hydraulically operated motors, which are not currently used in Naval elevator systems.

Sensor development currently should be directed toward existing systems. However, if closed loop systems should be contemplated, flux-gate magnetic sensors are capable of filling the need for error sensing devices.

Open Loop Systems

It is not the purpose here to discuss control systems but to anticipate the sensing requirements, and these cannot be divorced from the control system.

Flux-gate sensors can be designed for various indications by making use of two field components. For example, if a switch is to be activated over a sharply defined range of travel by the target along the z-axis, the necessary conditions for activation would be:

(a) the z-component has the proper polarity,

(b) the absolute magnitude of the x-component is less than a prescribed threshold level.

Figure 6 shows that, close to the target, variations in the distance, x, would have almost no effect on the resulting range of activation along the z-axis if it is a small fraction of the distance between magnetic poles.

A somewhat larger range of proximity is indicated by the sign of the z-component. This range is determined entirely by the pole spacing and distance of the magnet. Where desirable, the direction of approach or departure of the target can be indicated by the sign of the x-component.

Double Headed Sensor

In the method previously described, the exact range fixed by a given threshold level is dependent on the strength of the magnetized target and the sensitivity of the detector. For uniformity of results, these quantities must be specified and kept within certain tolerances, or the threshold level and/or sensitivity must be adjusted to meet specifications with the target used.

By using two sensing heads, it is possible to indicate a sharply defined narrow z-axis range of target proximity that, within limits, is virtually independent of the magnet strength, detector sensitivity, or distance along the x-axis. The length of this range is essentially the spacing between the two ring-cores.

The operating principle is simply that the x-component of magnetic intensity is simultaneously sensed at two locations having a fixed z-axis displacement. Since the x-component reverses sign at the $z = 0$ plane of the magnet, this component can have opposite signs at the two locations only when the $z = 0$ plane lies between them.

Detector circuitry for this scheme consists simply of a second harmonic phase comparator. The signal from the second sensing head takes the place of the reference voltage. The indication of proximity is given by a phase comparator output polarity that indicates opposite phases (and hence, unlike signs in the field intensities). The scheme is illustrated in Fig. 7.

It is estimated that by orienting the two ring-cores in parallel planes, they can be spaced as close as 1/4 in. apart. Thus, the sensor could be made to give an output signal whenever the center of the target is within ±1/8 in. of a fixed plane.

A sensor of this type would have good immunity from false indications (or triggering) by spurious magnetic fields because, for a close spacing between the sensing heads, the spurious field will generally have the same direction or sense at both of them.

Application with an Unmagnetized Iron Target

Induced Field

Use of a magnetometer to detect the presence of an iron or steel object which is not permanently magnetized involves detection of changes in an ambient or imposed magnetic field by the disturbing influence of the object. The disturbance is caused by the phenomenon of induced magnetism, whereby the iron becomes magnetized in an external magnetic field. It is understood that, due to retentivity, all iron and steel is weakly magnetized, but it is assumed that the magnetizing field is strong enough that the induced magnetization is stronger than the residual.

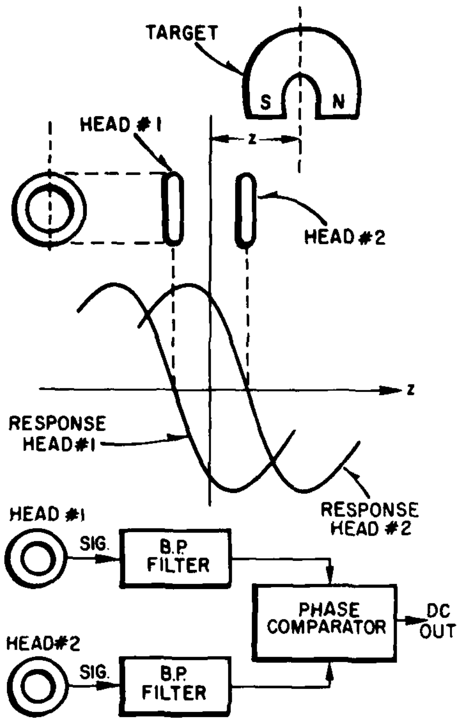


Fig. 7 — Magnetic sense comparison with two heads

To provide the necessary magnetizing field, a magnetic sensor for detecting unmagnetized iron or steel targets must incorporate an internal magnet. The field resulting from the induced magnetization of the target is then superimposed by vector addition on the field of the magnet and the target is sensed by the changes that occur in the resultant field.

Magnetic Bridge

The sensor can be made sensitive to small changes resulting from the induced field by a geometrical arrangement of the magnet, the field sensitive element, and soft iron parts which cancel the direct effect of the magnet on the field sensitive element. The arrangement will be designated as a "magnetic bridge" because it is analogous to an electrical bridge circuit.

The geometry of the magnetic bridge and the electrical analogy are shown in Fig. 8. In the electrical circuit, electric currents and resistances are analogous to the magnetic flux and reluctances (air gaps) respectively in the flux paths of the magnetic bridge. The magnetic sensing element is directionally sensitive, however, and its directional axis must be oriented as indicated by the arrows in the diagram for the analogy to be valid.

By analogy, the conditions for balance of the magnetic bridge are readily apparent. The magnetic flux, through the sensing element, is nulled by sliding the soft iron bar (nearest the magnet) laterally in front of the magnet's poles to adjust the reluctance ratio R_1/R_2. The sensor is normally balanced with no iron or steel nearby.

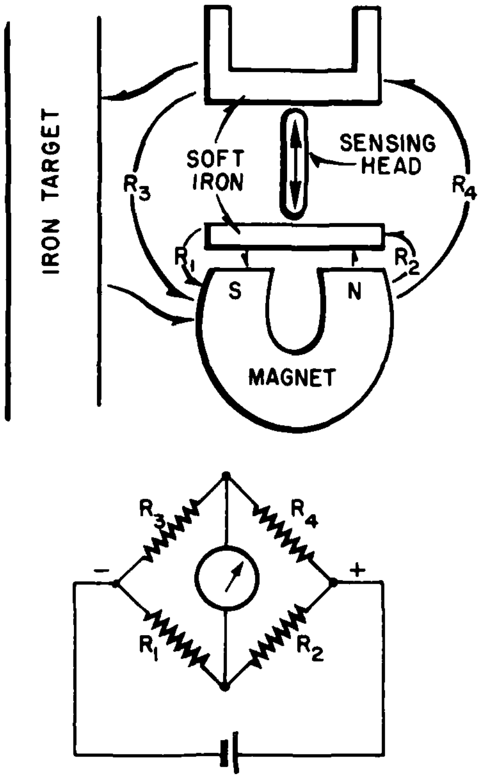


Fig. 8 — Magnetic bridge and electrical analogy

The proximity of an iron target, as shown in the diagram, decreases the reluctance, R_3, of the large air gap nearest the target, unbalancing the bridge to give a magnetic indication by the sensing element.

Results

As expected, the response to an iron target is dependent on the target distance from the magnetic gap in the bridge. Relative to a plane, the target's position is not sharply defined. The operating range of such a device must be determined by a threshold level.

If the side of the sensor opposite the target is near a steel bulkhead or mounting plate, the bridge is unbalanced in the reverse direction unless the target is closer to the sensor than the mounting plate. With a sensor that is sensitive to the sign as well as the amplitude of the magnetic field, the proximity switch will not be activated by the steel mounting plate. Thus, the required target range is automatically decreased to a distance less than the distance to any steel plate on the side of the sensor opposite the target.

A similar desensitizing effect exists in the Go-switch. The target sensing characteristics of the two devices are similar.

Unlike the Go-switch, the flux-gate magnetic detector itself has no hysteresis whether used with an active or a passive target, but a hysteresis is inherent to some degree in the triggering circuits that would be used for threshold detection. A degree of hysteresis is generally considered desirable for noise immunity.

CONCLUSIONS

This investigation has revealed that the use of dc or permanent magnetism for detection by shipboard elevator sensors is practical and has many desirable features. By application of the operating principle of flux-gate magnetometers, practical detection devices may be designed to meet a variety of sensing requirements.

Use of a permanently magnetized target allows precise vertical proximity range detection, level plane detection, and vertical error sensing. Detection of iron or steel "passive" targets is less precise than is possible with magnetized targets but can also be implemented with the flux-gate principle.

A flux-gate proximity sensor for passive targets would have range characteristics similar to a magnetic proximity switch currently in use (the Go-switch), but has the advantage of no moving parts and latitude in the selection of range and desired hysteresis.

A sensor using the flux-gate principle with a magnetized target offers both precision and alternative types of position indications for greater flexibility in the development of new control concepts.

RECOMMENDATIONS

It is recommended that a magnetic flux-gate sensor type be selected, designed and a prototype engineered under contract. Selection of the sensing mode and specifications of output circuitry should be based on compatibility with an existing elevator control system in which it may be evaluated.

Laboratory tests for sensitivity and repeatability, and certification testing for shock, vibration, and radiation should precede final shipboard evaluation.

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